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Chemical Vapor Composite Silicon Carbide for Space Telescopes (Postprint)

Clifford Tanaka
Kyle Webb

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Conference Proceedings

AIR FORCE RESEARCH LABORATORY
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14. ABSTRACT

The Purpose of this figure study was to demonstrate the optical figure and opto-mechanical performance capabilities for Trex's CVC SiC material. In the course of this activity a plano mirror was designed, fabricated, polished, and analyzed using interferometry tools and methods. The opto-mechanical and interferometric performance results are presented and analyzed in this report.

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Chemical Vapor Composite Silicon Carbide for Space Telescopes

AFRL Phase 2 SBIR

Clifford T. Tanaka / Kyle Webb

Trex Enterprises Corporation

Chemical Vapor Composite Silicon Carbide for Space Telescopes
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  - General Optics for optical metrology.
  - 3D-Engineering Corp. for Finite Element Analysis.
  - ATA Engineering Corp. for modal testing.
  - Ormond, LLC for water jet milling.

Chemical Vapor Composite Silicon Carbide for Space Telescopes Overview

- **Goal: Produce a 750mm aperture CVC SiC mirror for the Advanced Relay Mirror System (ARMS)**
- **Tasks:**
  - 150mm CVC SiC Plano Mirror Figure Study
    - Demonstrate fabrication of a stiff, high quality lightweighted mirror
    - Compare modeled FEA modal performance vs. experimental measurements
  - Evaluation of HEL coatings on CVC SiC coupons
  - 750 mm CVC SiC mirror design & fabrication
- **Status:**
  - 150 cm CVC SiC Mirror analysis completed.
  - HEL coating evaluation underway.
  - 750 mm CVC SiC mirror design completed. Fabrication in 2007.

Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror Figure Study

- The purpose of this figure study was to demonstrate the optical figure and opto-mechanical performance capabilities for Trex's CVC SiC material.
- In the course of this activity a plano mirror was designed, fabricated, polished, and analyzed using interferometry tools and methods.
- The opto-mechanical and interferometric performance results are presented and analyzed in this report.

Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror

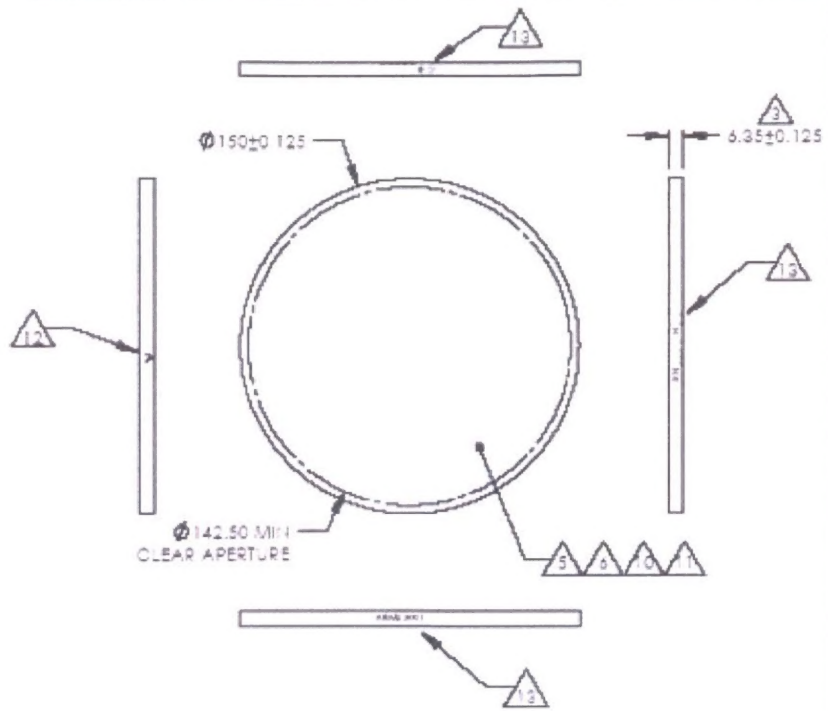
- **The following specifications were established to bench mark the optical and opto-mechanical performance in this effort:**
  - Surface Figure:
    - Plano surface: 150mm outside diameter with a 95% clear aperture
    - Peak to Valley reflected wave front error: < λ/10 at 632.8 nm
  - Surface Roughness: < 20 Å rms.
  - Areal Density: </= 10 kg/m^2
  - Modal Frequency Specification: >/= 1500 Hz in free-state
  - Ultra-Light-Weight, Open Back, Iso-Grid Mechanical Configuration: </= 200 grams
- **Design Approach:**
  - Finite Element Analysis (FEA) tools were used extensively to formulate an aggressive opto-mechanical design that would test the limits of the CVC SiC material as it is applied to challenging optical figure polishing processes.
  - Sensitivities associate with self-weight-sag and print-through or quilting were anticipated to be revealed and studied.

Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror
150mm Mirror Detailed Design (sheet 1 of 2)

NOTES: (UNLESS OTHERWISE SPECIFIED)

1. APPLICABLE STANDARDS/SPECIFICATIONS
   A) ASME Y14.5M-1994 (DIMENSIONS AND TOLERANCES)
   B) 49-20-ES096 (LATEST REVISION): DRAWING INTERPRETATION
2. MATERIAL: TREX CVC SiC
3. WEDGE: < 1 ARC MINUTE
4. CHAMFER ALL EDGES TO 0.25±0.10 X 45°±10°
5. CLEAR APERTURE: MIN 95% OF OD
6. SCRATCH DIG 40-20 OR BETTER PER MIL-PRF-13830, OVER CLEAR APERTURE
7. EDGE CHIPS TO BE STONED AND NOT TO EXTEND INWARD BEYOND 1.0
8. SURFACES ARE TO BE FINE GROUND
9. ST RADIUS: ∞ (PLANO)
10. PEAK-TO-VALLEY REFLECTED WAVEFRONT ERROR < λ/10 AT 632.8 nm, SURFACE ROUGHNESS < 20 ANGSTROMS RMS, OVER CLEAR APERTURE
11. COATING: TBD, R>99.99% AT 1.064 MICRONS
12. IDENTIFY REFLECTIVE COATING SURFACE AS "V" APPROXIMATELY WHERE SHOWN, USING NON-PARTICLE GENERATING, INORGANIC MARKING MATERIAL
13. IDENTIFY WITH TREX PART NUMBER, RU NUMBER, AND ID NUMBER APPROXIMATELY WHERE SHOWN, USING NON-PARTICLE GENERATING INORGANIC MATERIAL. TEXT MUST BE CLEAR AND LEGIBLE WITHOUT MAGNIFICATION.
    NUMBERS CONTAIN THE FOLLOWING:
    RN = COATING RUN NUMBER (X####) WHERE X = CHAMBER ID (E.G. A=1, B=2, ETC.
    AND #### = UNIQUE RUN ID AND H = HOLDER NUMBER
    D = MATERIAL LOT ID NUMBER
14. CLEAN PART AND PACKAGE USING CLEAN, NON-OUTGASSING, PARTICLE FREE MATERIAL. INCLUDE DESICCANT IN DOUBLE-BAG PACKAGING. OPTIC IS TO BE PACKAGED SUCH THAT NO MATERIAL, INCLUDING LENS TISSUE, CONTACTS THE OPTIC WITHIN THE CLEAR APERTURE
15. PARTS TO BE PACKAGED INDIVIDUALLY AND LABELED ON THE OUTER SURFACE OF THE PACKAGE WITH TREX PART NUMBER AND CODE NUMBER THE SAME AS IN NOTE 12
16. THE FOLLOWING DOCUMENT MUST BE SUPPLIED FOR EACH SERIALIZED PART (ELECTRONIC DATA PREFERRED): REFLECTION SPECTRUM FOR EACH COATING RUN
17. MANUFACTURING METHODS, EQUIPMENT, AND MATERIALS THAT ARE USED TO FABRICATE THIS PART ARE NOT TO BE CHANGED AFTER TREX QUALIFICATION, WITHOUT WRITTEN APPROVAL
18. DIMENSIONS ARE IN MILLIMETERS

REVISIONS				
REV	ZONE	DESCRIPTION	DATE	APPROVED
INC		INITIAL ISSUE	6/27/2005	
A		UPDATED NOTES	7/11/2006	



DO NOT SCALE DRAWING

DRAWN	P. WHITE	6/27/2005
ENGINEER	P. WHITE	6/27/2005
CHK'D		
APP'D		
MFG		

MATERIAL: N/A

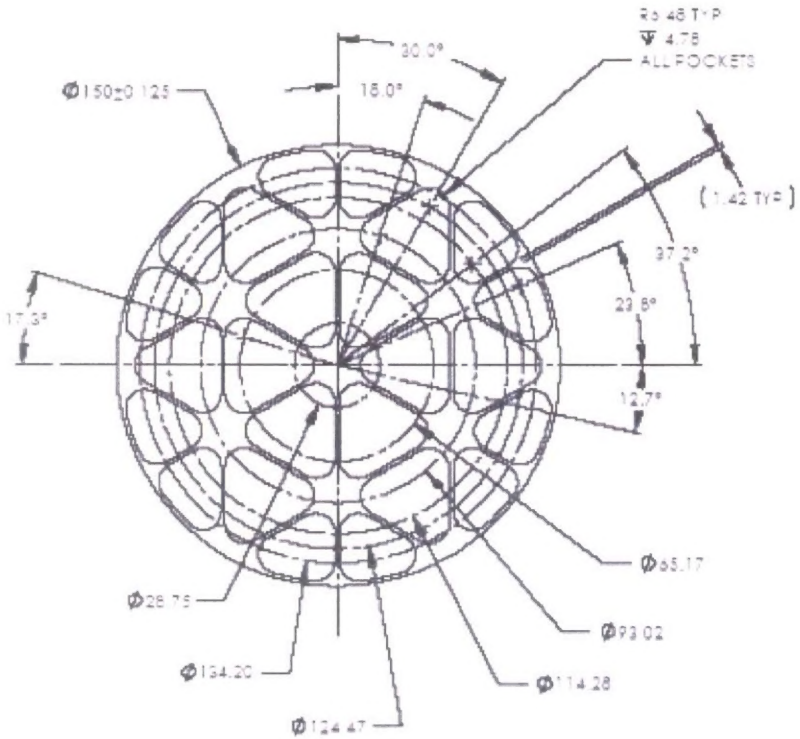
TREX ENTERPRISES

ARMS
150 mm MIRROR

SIZE	CAGE	DRAWING NO.	REV
B	0ZKJ6	ARMS 3001	A

SCALE: | TOOLMAKER'S Ø: 155.501 | SHEET 1 OF 2

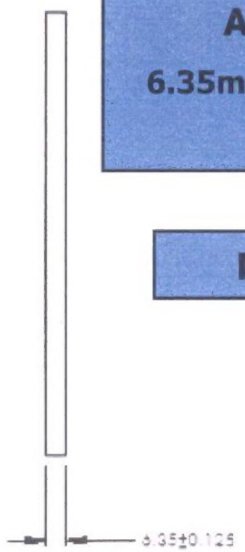
Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror
150mm Mirror Detailed Design (sheet 2 of 2)



Face Sheet Thickness:
6.35mm – 4.78mm = 1.57mm

Aspect Ratio:
6.35mm/150mm = .0423
(23.62 to 1)

Mass: 155gr



NOTES:
1. ASSUME SYMMETRY OF DIMENSIONS
2. 60° SEPARATION BETWEEN CORRESPONDING FEATURES

DO NOT SCALE DRAWING

P. WHITE 6/27/2006
P. WHITE 6/27/2006

TREX ENTERPRISES

ARMS
150 mm MIRROR

SIZE	CAGE	DRAWING NO.	REV
B	0ZKJ6	ARMS 3001	A

N/A 155.501 SHEET 2 OF 2

TREX ENTERPRISES
HAWAIIAN OPERATIONS

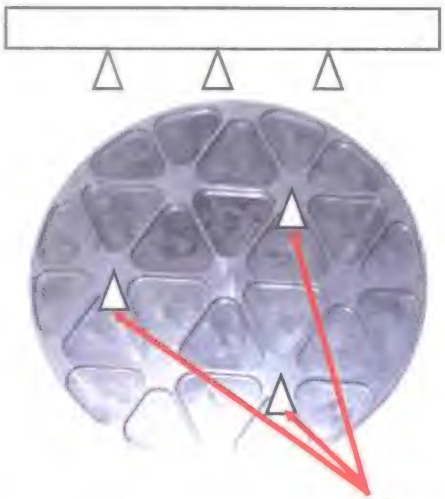
Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror
Interferometer Measurement Configurations

- **Horizontal:**
  - Three Point Supported at Iso-Grid Nodes
  - Supported on Tissue Paper
  - Supported at center Iso-grid Node
  - Three Point support at Mirror Edge

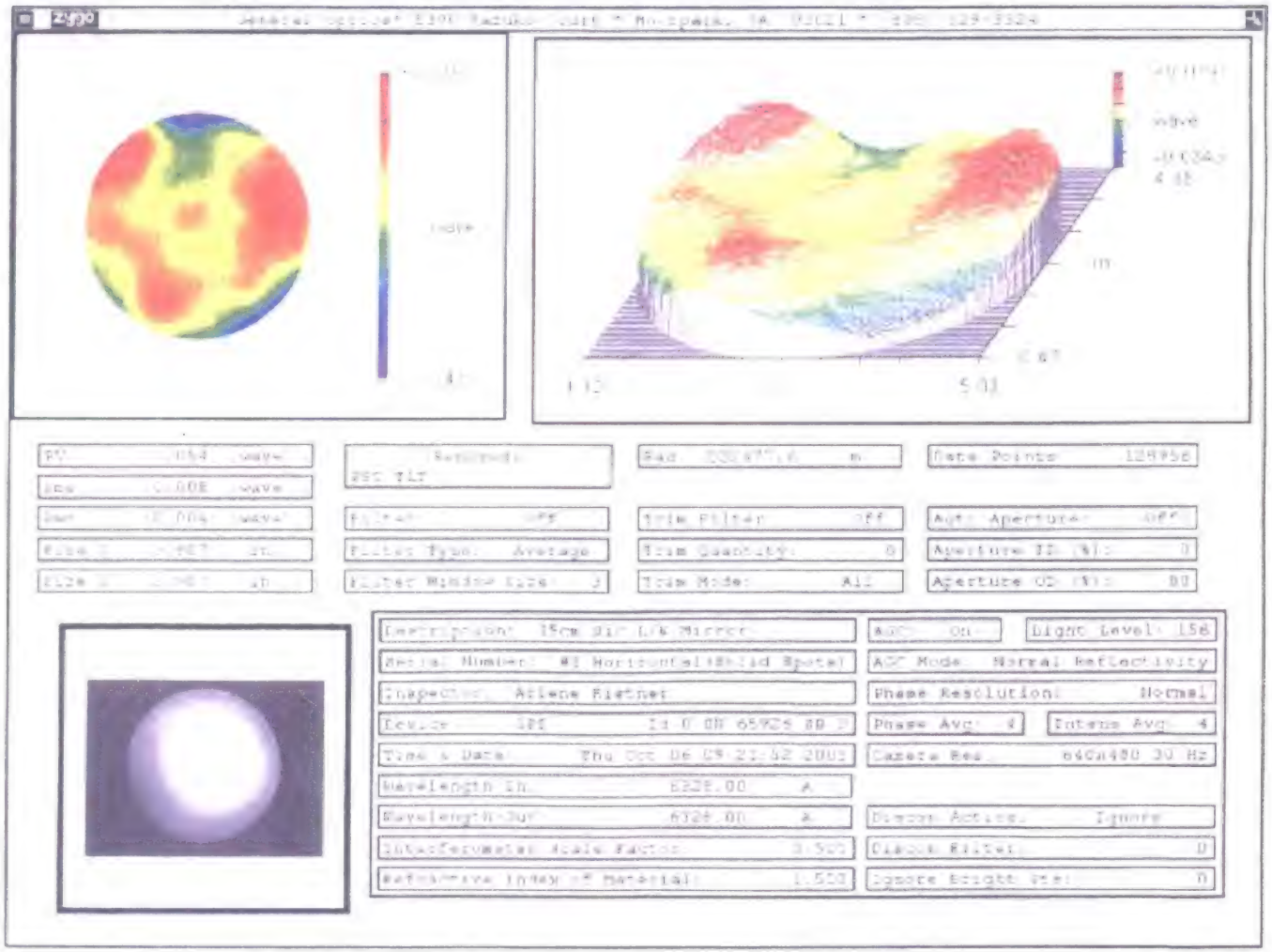
- **Vertical:**
  - Edge mounted on a V block
  - Edge mounted on a V block and rotated from original measured position.
  - Edge mounted on a V block and rotated again from the last measured position.

Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror
Horizontal, Three Point Support at Iso-Grid Nodes

- **Interferometer Performance:**
  - pv 0.054 waves (λ/19)
  - rms0.008 waves (λ/125)
  - Pwr -0.004 waves
- **Measurement Orientation:**
  - Horizontal (flat on optical table)
  - Mirror supported from point contacts on 3 iso-grid nodes
  - Produces best results on interferogram for this mounting orientation.



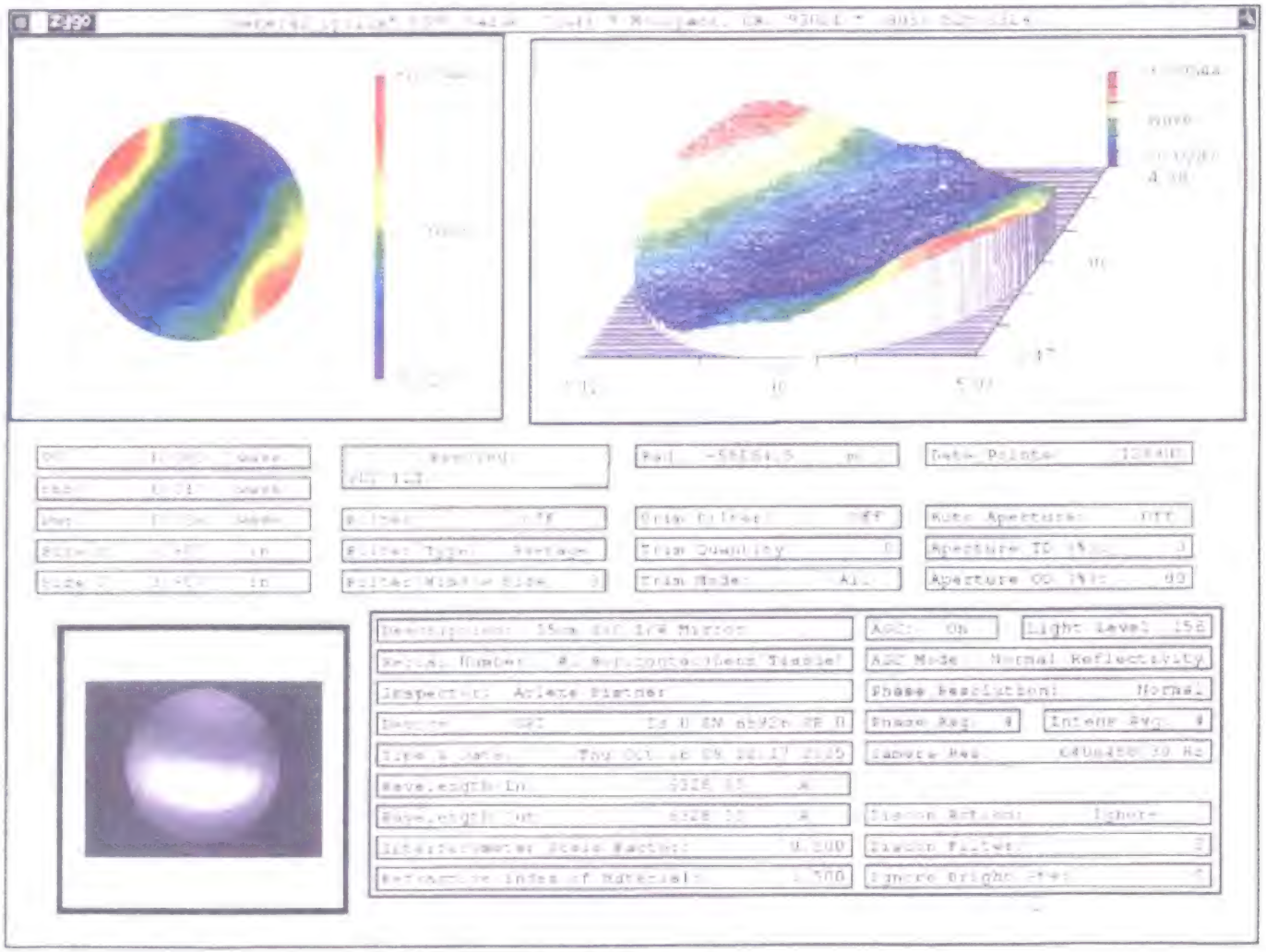
Three point support on iso-grid nodes

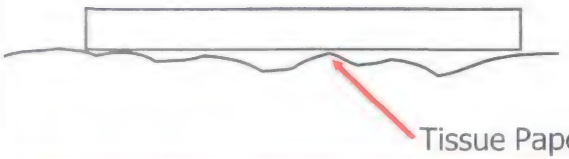


ENTERPRISES
HAWAIIAN OPERATIONS

Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror
Horizontal, Mounted on Tissue Paper

- **Interferometer Performance:**
  - pv 0.083 waves (λ/12)
  - Rms 0.017 waves (λ/59)
  - Pwr 0.034 waves
- **Measurement Orientation:**
  - Horizontal (flat on optical table)
  - Mirror supported with tissue paper only.
  - Produces classic potato chip shape interferogram.

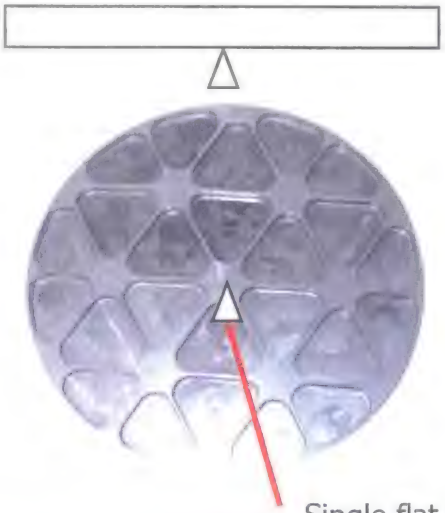




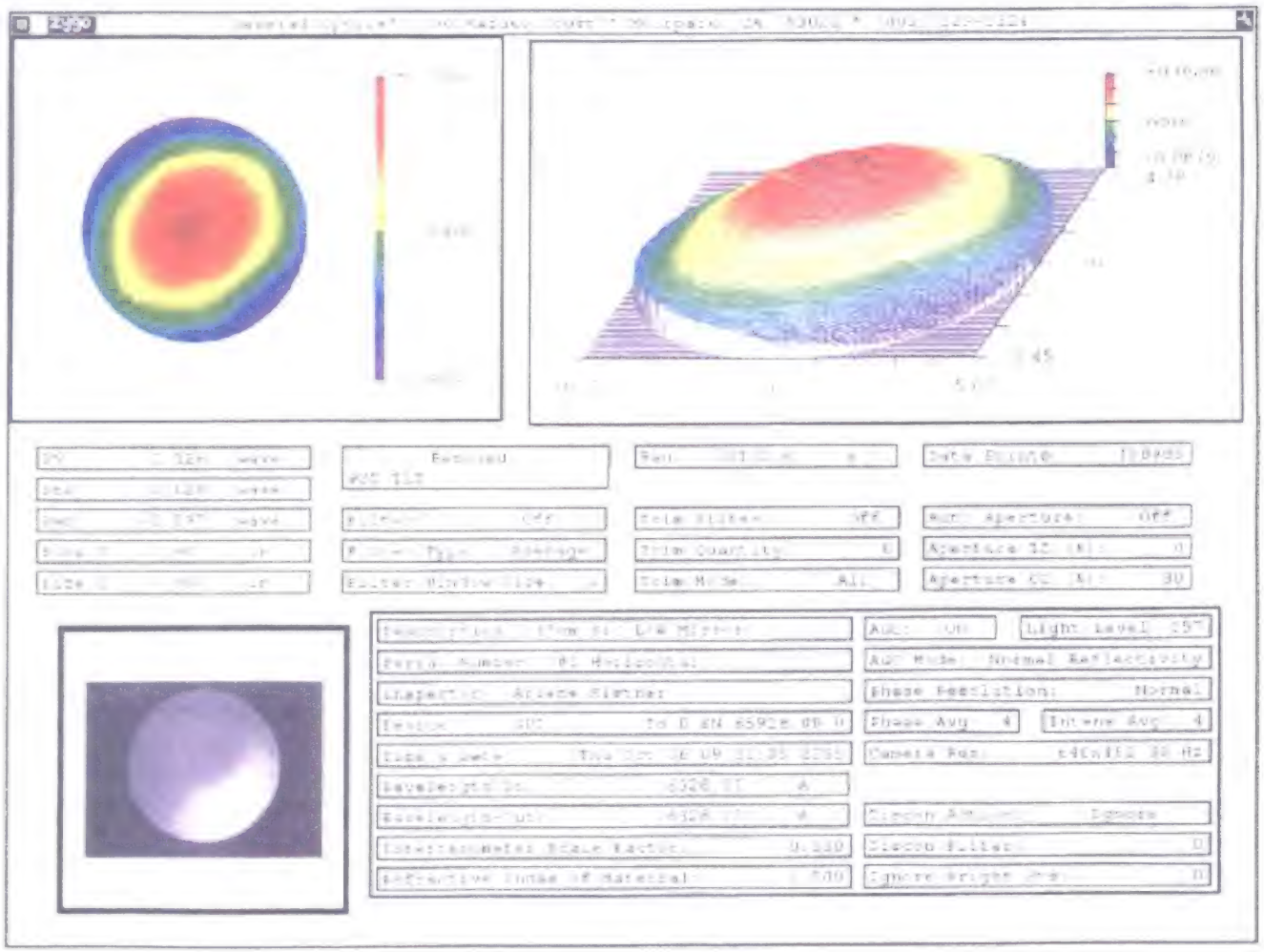
ENTERPRISES
HAWAIIAN OPERATIONS

Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror
Horizontal Mount, Single Flat Contact Point at Center

- **Interferometer Performance:**
  - pv 0.126 waves (λ/8)
  - rms0.029 waves (λ/34)
  - Pwr -0.097 waves
- **Measurement Orientation:**
  - Horizontal (flat on optical table)
  - Mirror supported at the center iso-grid node flat o the back side only.
  - Produces a convex shape as seen in the interferogram.

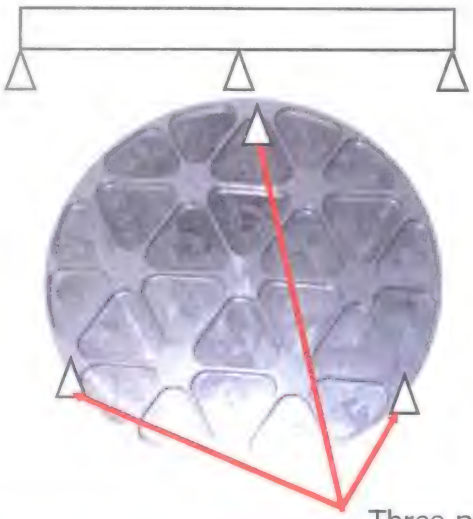


Single flat contact support at center Iso-grid node

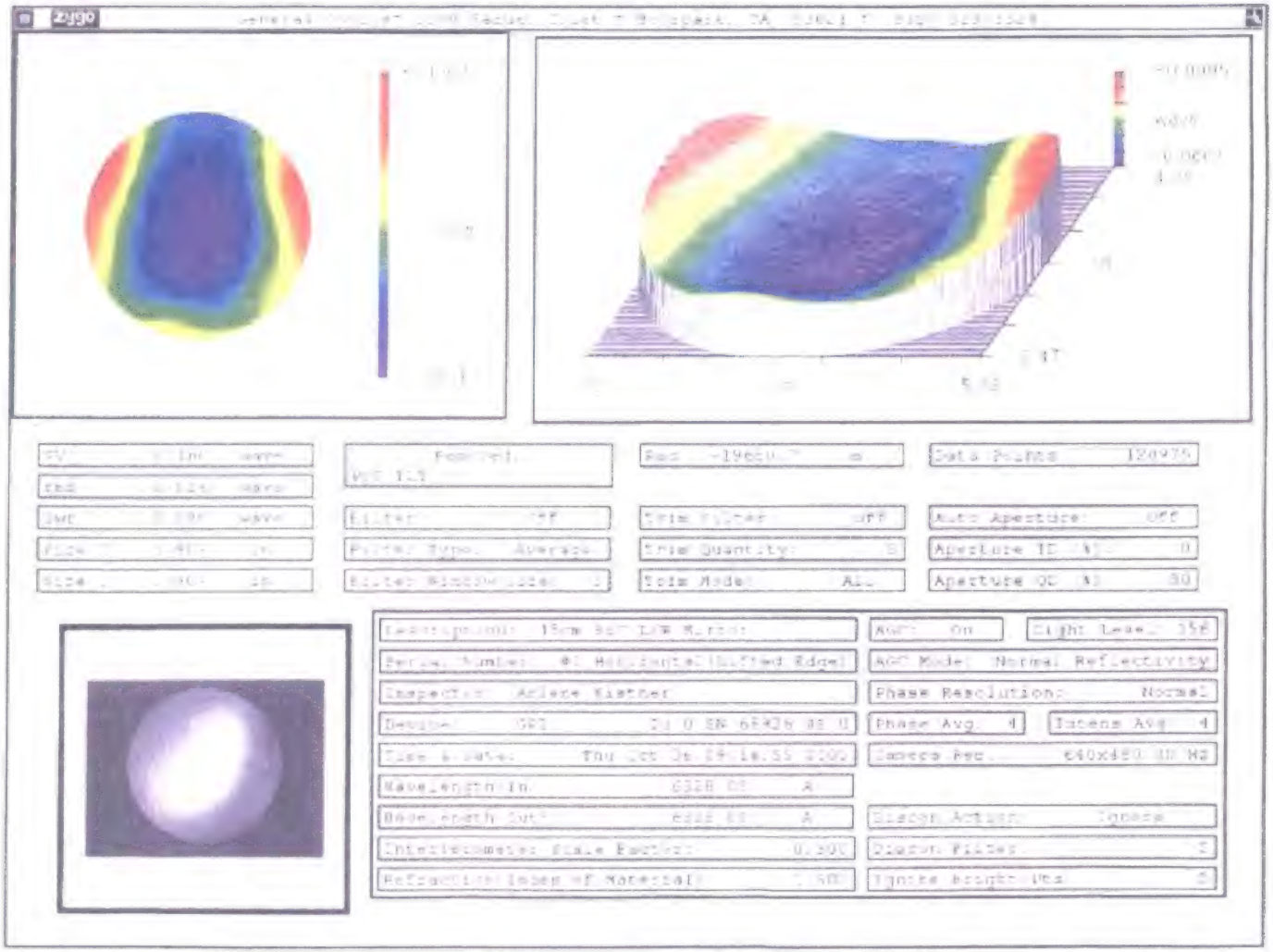


Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror
Horizontal Mount, Three Point Support at Edge

- **Interferometer Performance:**
  - pv 0.160 waves (λ/6)
  - rms 0.034 waves (λ/29)
  - Pwr 0.099 waves
- **Measurement Orientation:**
  - Horizontal (flat on optical table)
  - Mirror supported with 3 point contacts at perimeter edge
  - Produces lifted edge or concave profile on interferogram.

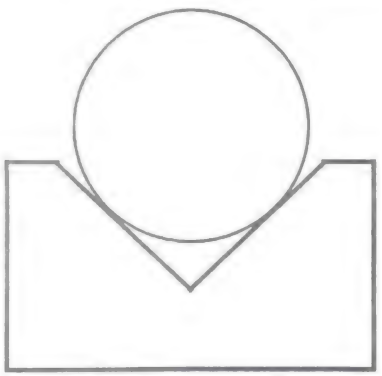


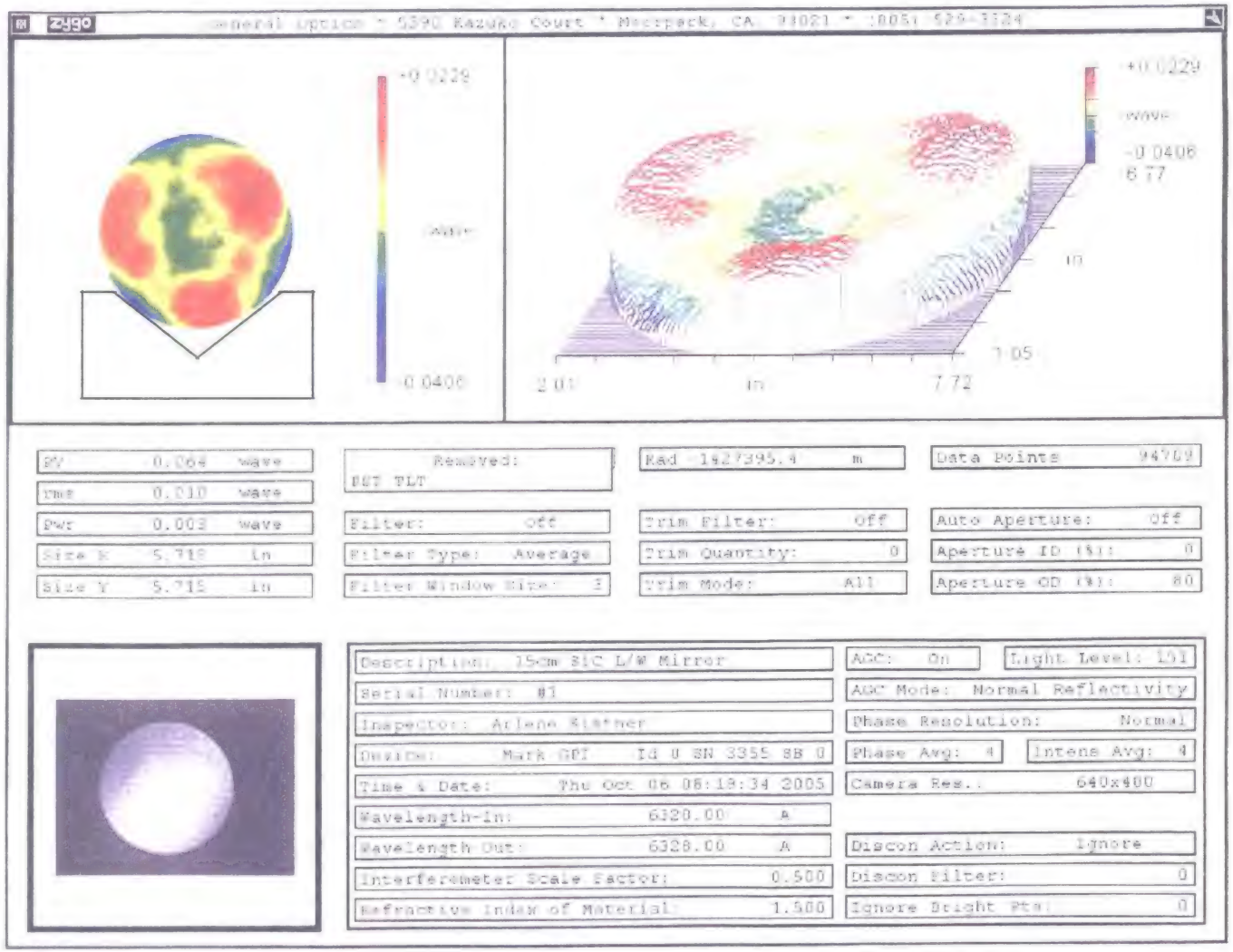
Three point edge support configuration



Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror
Vertical Mount, V-Block

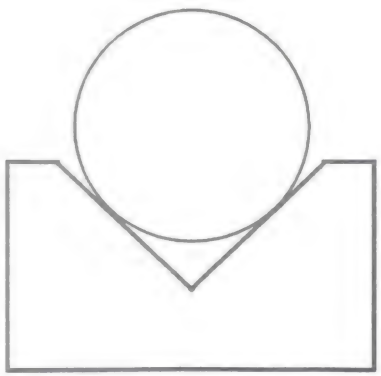
- **Interferometer Performance:**
  - pv 0.064 waves (λ/16)
  - rms0.010 waves (λ/100)
  - Pwr 0.003 waves
- **Measurement Orientation:**
  - Vertical (V-Block support)
  - V-Block oriented in norma configuration as viewed ir interferograms.
  - Produces best results on interferogram for this mounting orientation.

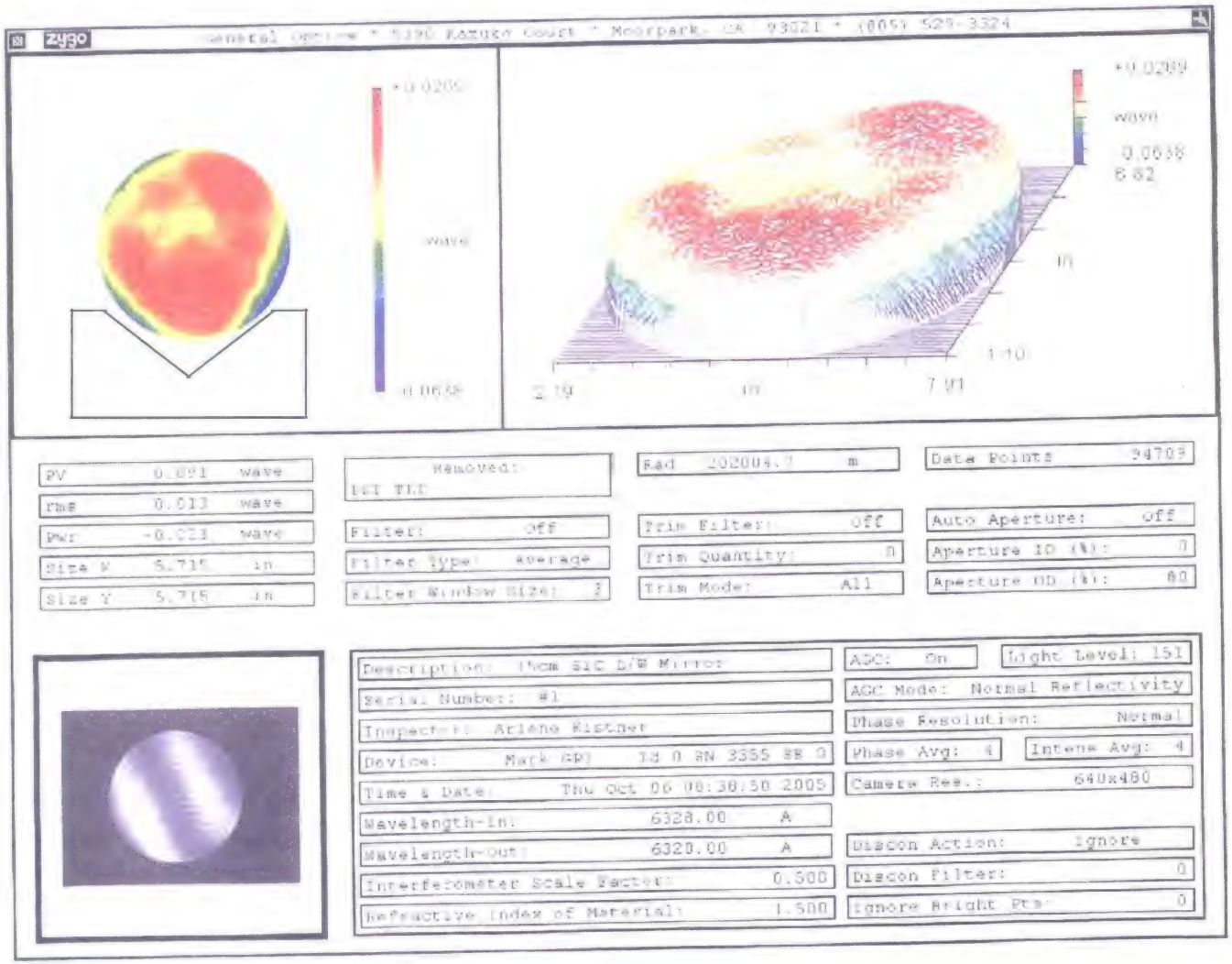




Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror
Vertical Mount, V-Block (rotated)

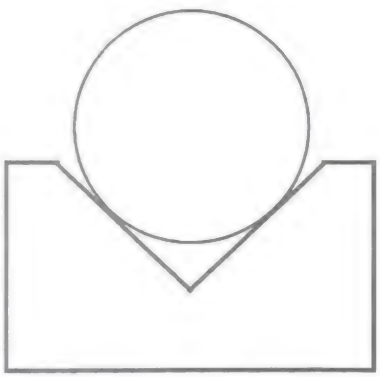
- **Interferometer Performance:**
  - pv 0.091 waves (λ/11)
  - rms0.013 waves (λ/77)
  - Pwr -0.021 waves
- **Measurement Orientation:**
  - Vertical (V-Block support)
  - V-Block oriented in normal configuration as viewed in interferograms.
  - Rotated from previous position.

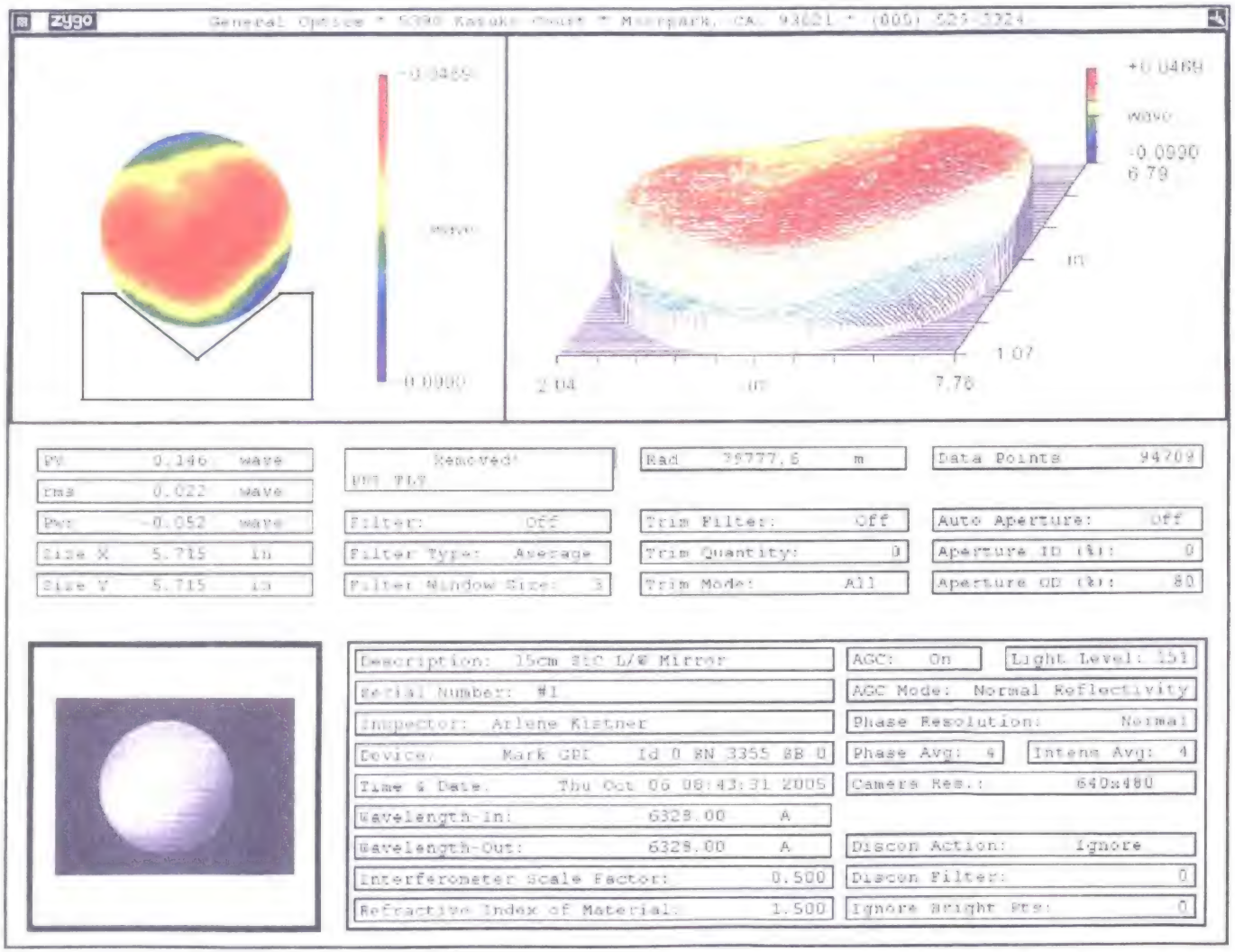




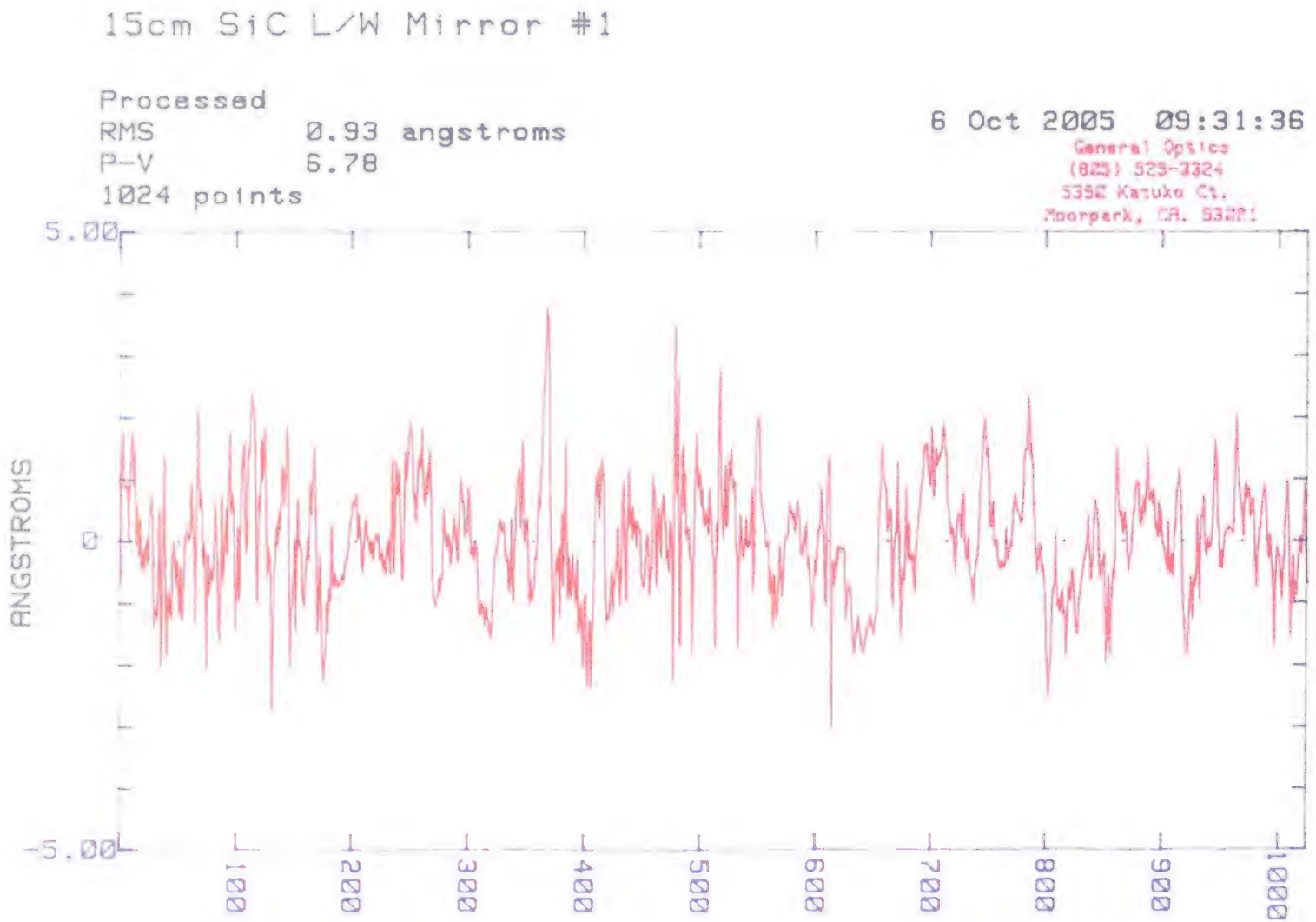
Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror
Vertical Mount, V-Block (rotated again)

- **Interferometer Performance:**
  - pv 0.146 waves (λ/7)
  - rms0.022 waves (λ/45)
  - Pwr -0.052 waves
- **Measurement Orientation:**
  - Vertical (V-Block support)
  - V-Block oriented in norma configuration as viewed ir interferograms.
  - Rotated again from previous position.





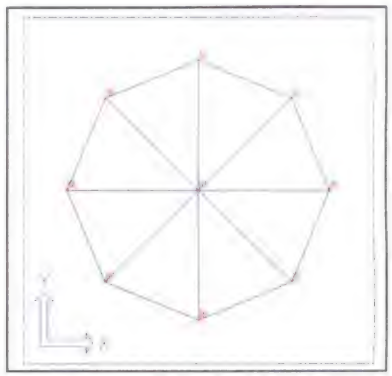
Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror
Surface Roughness via Zygo



ENTERPRISES
HAWAIIAN OPERATIONS

Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror
Modal Analysis

- **Test was perform via classical ping test protocol.**
  - Foam bed used to simulate free state mode.
  - Tiny hammer accelerometer & response accelerometer.
  - Ping responses were collected from nine (9) points depicted in schematic (in figure at right).
  - Software program transformed responses into wire plots of mode shapes as presented in earlier slides
- **Comparison made to Finite Element Analysis Results**



Wire Frame Schematic of Ping Test Points on Mirror

Test Setup Showing Foam Bed & Tiny Hammer Accelerometer

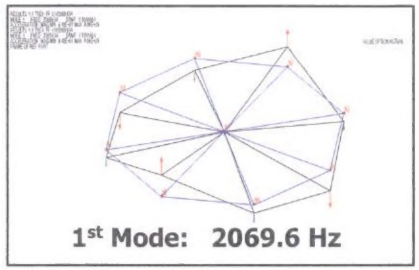
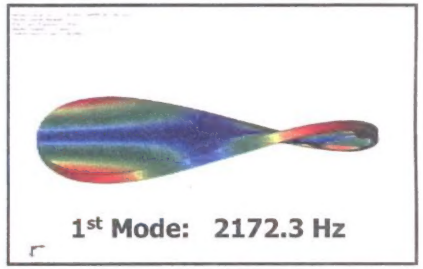
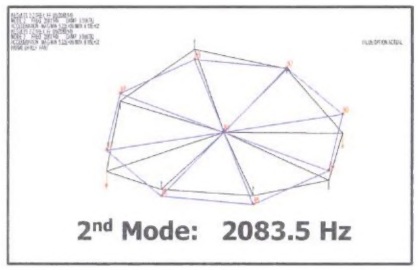
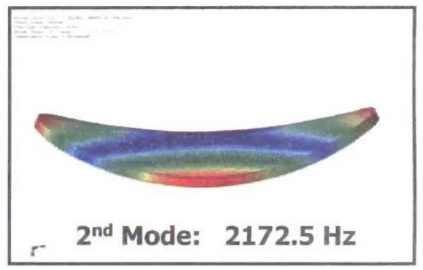
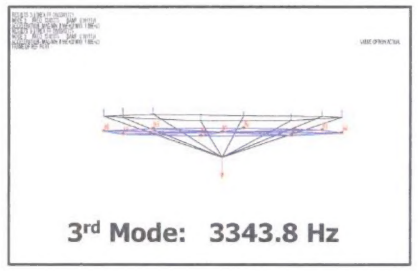
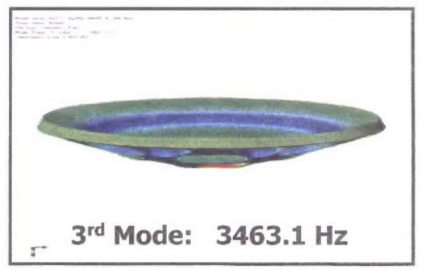
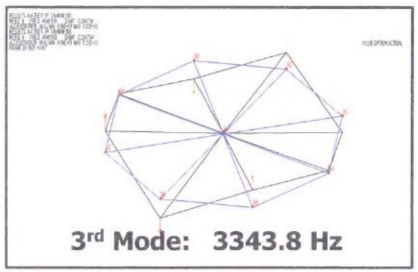
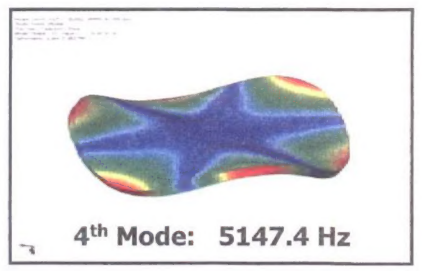
Hammer Accelerometer Shown as Tested

Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror
Modal Analysis Results

- A close correlation is established between the predicted modal values and the actual measured modal values
- Variance in higher modes can be attributed to:
  - Difference between theory and reality.
  - Constraint conditions in FEA model can not exactly duplicate actual constraint system as tested (foam bed).

Predicted	
Mode	Hz
1st	2172.3
2nd	2172.5
3rd	3463.1
4th	5464.1

Measured	
Mode	Hz
1st	2069.6
2nd	2083.5
3rd	3343.8
4th	4646.9

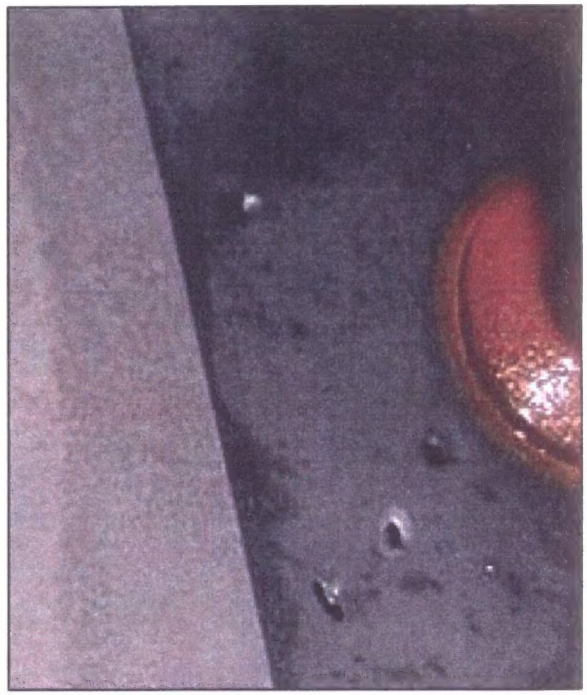
Measured	Predicted
 1st Mode: 2069.6 Hz	 1st Mode: 2172.3 Hz
 2nd Mode: 2083.5 Hz	 2nd Mode: 2172.5 Hz
 3rd Mode: 3343.8 Hz	 3rd Mode: 3463.1 Hz
 3rd Mode: 3343.8 Hz	 4th Mode: 5147.4 Hz

Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror
Water Jet Cutting of CVC SiC

- **Development of water jet cutting and milling process have proven to be feasibility for fabrication:**
  - Demonstrated Water Jet Cutting and Piercing Processes:

Water Jet Cutting Through 1.3" of CVC SiC Material

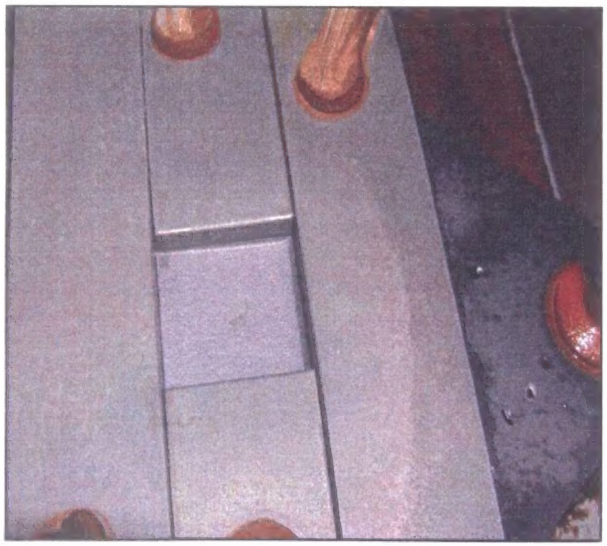
Initial Water Jet Piercing Through .5" of CVC SiC Material



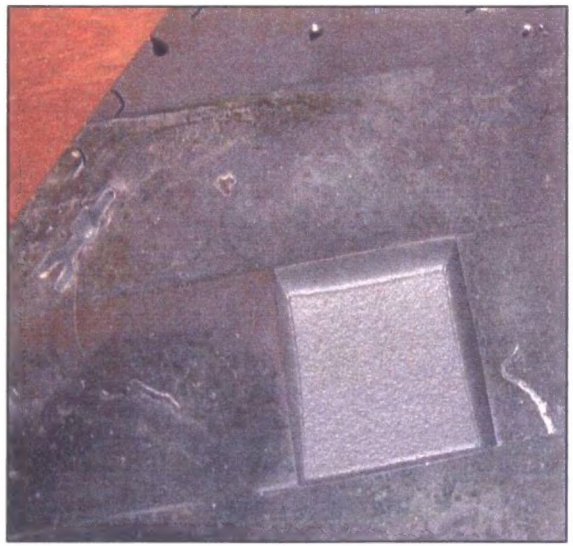
Water Jet Piercing Through 1.3" of CVC SiC Material

Chemical Vapor Composite Silicon Carbide for Space Telescopes
150mm CVC SiC Plano Mirror
Water Jet Milling of CVC SiC

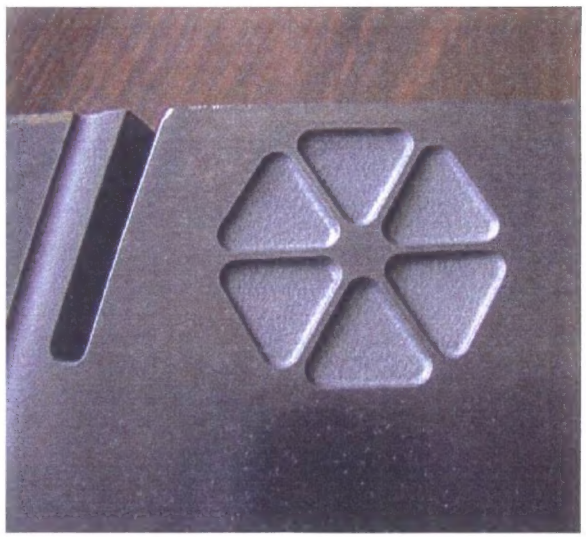
- **5 Axis water jet milling capability has been established:**
  - Demonstrated water jet milling process:
    - Current process produces punch through of 1.3" thick CVC SiC material in 40 seconds
    - Cutting rates of over 1 linear inch per minute on 1.3" material have been demonstrated.
    - Milling rates of .010" per pass have been demonstrated.



Water Jet Milling Simple Masking Setup



Water Milling of 25mm by 25mm Square by 4mm Deep Pocket in CVC SiC Material



Water Milling of Isogrid for lightweighting of CVC SiC

Chemical Vapor Composite Silicon Carbide for Space Telescopes
Summary

- CVC Silicon Carbide is an ideal optical material, with high specific stiffness, superior thermal stability, polishability and low residual stress.
- 15cm plano CVC SiC mirror with excellent stiffness, surface figure and surface roughness has been demonstrated.
- Experimental and theoretical modal analysis show that CVC SiC components can be readily designed & modeled.
- Trex is proceeding with 750mm aperture mirror fabrication, to be completed in 2007.